

PROTOCOL

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# Effects of transcranial direct current stimulation on mental fatigue reduction and physical performance improvement in healthy adults: a systematic review protocol

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## Abstract

**Background** Mental fatigue (MF) is a psychobiological state that impairs physical and cognitive performance, particularly in endurance and resistance tasks. Transcranial direct current stimulation (tDCS) has emerged as a promising noninvasive neuromodulation technique to mitigate MF and increase exercise capacity. However, evidence remains inconsistent due to methodological heterogeneity in stimulation parameters, fatigue induction protocols, and outcome assessments. This research aims to systematically review randomized controlled trials (RCTs) investigating the effects of active versus sham tDCS on reducing MF and improving physical performance, such as time to exhaustion and muscular endurance, in healthy, physically active adults, including athletes.

**Methods** This protocol follows the PRISMA-P guidelines and is registered with PROSPERO (CRD4202541050229). Eligible studies will include RCTs (parallel or crossover) comparing active tDCS (any validated protocol) with sham stimulation in adults  $\geq 18$  years of age without neurological, psychiatric, or cardiovascular conditions. Searches will be conducted in PubMed, Embase, Scopus, Web of Science, SPORTDiscus, PsycINFO, and ClinicalTrials.gov. Primary outcomes are time to exhaustion and number of repetitions to failure; secondary outcomes include MF scores. Two independent reviewers will select studies, extract data, and assess risk of bias using Cochrane RoB 2.0. Metaanalyses will be performed where possible, with subgroup, sensitivity, and metaregression analyses as appropriate.

**Discussion** This review will synthesize the available evidence on the efficacy of tDCS on MF and physical performance in healthy adults. The results aim to inform the design of future research and support the standardization of tDCS protocols in sport and exercise science.

**Systematic review registration** PROSPERO CRD420251050229

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## Background

Sports performance has been extensively investigated through experimental clinical trials, observational studies, and systematic reviews to enhance physical and cognitive capabilities and improve outcomes in competitive settings [1–3]. Among the various factors that influence athletic performance, mental fatigue (MF) stands out. MF is a transient state of reduced cognitive and executive functioning resulting from prolonged and intense mental effort [4, 5]. This condition manifests through subjective symptoms of tiredness, decreased motivation, and difficulty concentrating, assessed by self-report instruments, such as the visual analogue scale (VAS) for mental fatigue, and by performance changes in attention and information-processing tasks [4–6]. MF is associated with increased ratings of perceived exertion (RPE), decreased time to exhaustion in endurance tasks, and reduced total work volume in muscular resistance tasks, typically measured by fewer repetitions until failure [5, 7–9].

Multiple factors may trigger MF, such as high work demands, information overload, prolonged concentration, physical exercise, and repetitive tasks, all of which lead to sensations of tiredness, decreased motivation, and heightened distractibility—ultimately impairing executive control and decision-making [10–12]. In the sports domain, the impact of MF varies depending on task intensity: it tends to be more pronounced in endurance activity at low- and moderate-intensity and less evident in short duration at high intensity [13–16].

Given the cognitive and motor impairments induced by MF, there is increasing interest in techniques capable of modulating brain activity, such as transcranial direct current stimulation (tDCS) [3, 17, 18]. tDCS delivers low-intensity electrical currents through scalp-mounted electrodes, promoting membrane depolarization with anodal stimulation and hyperpolarization with cathodal stimulation [17–20]. Anodal stimulation protocols targeting the dorsolateral prefrontal cortex (DLPFC) and the primary motor cortex (M1) have shown reductions in RPE and improvements in endurance and muscular performance by extending time to failure [21–23].

However, the literature presents mixed results. For instance, Holgado et al. [24] found no significant performance enhancement in trained cyclists receiving tDCS over the DLPFC, while Penna et al. [25] reported no ergogenic effect in master swimmers. These findings suggest that variables such as stimulation site, current intensity, and participant characteristics may influence the technique's efficacy [24, 25]

Despite promising findings, such as increased training volume [23] and prolonged time to exhaustion [21], the heterogeneity of tDCS protocols complicates cross-study

comparisons and evidence consolidation [3]. This variability includes key parameters such as current intensity [18], stimulation duration [17, 26], electrode montage and placement [3, 27], and outcome selection [17]. Similarly, other investigations have failed to demonstrate consistent benefits of tDCS in endurance tasks or resistance-based protocols [24, 25, 28, 29]. These findings suggest that stimulation site, current density, individual training level, and prior exposure to tDCS may modulate its efficacy.

The diversity of tDCS protocols (intensity, duration, and montage) and mental fatigue induction methods, along with inconsistent results, precludes the definition of optimal parameters for reliable modulation. Although previous reviews have assessed the effects of tDCS on physical performance or examined factors related to MF separately, no systematic review has concurrently evaluated tDCS, MF, and physical performance in healthy adults, including athletes. In light of these considerations, this protocol aims to systematically review randomized controlled trials comparing active versus sham tDCS in reducing MF and improving time to exhaustion and repetitions to failure in healthy adults.

## Methods

### Protocol and registration

This protocol was developed according to the guidelines of the Preferred Reporting Items for Systematic review and Meta-Analysis Protocols (PRISMA-P) [30] and registered with PROSPERO (CRD420251050229).

### Eligibility criteria

Only randomized controlled trials (parallel or crossover designs) comparing active tDCS, conducted according to validated protocols targeting any brain region, with sham stimulation, will be included. Participants must be physically active adults (recreational or athletes), aged  $\geq 18$  years, with no neurological, psychiatric, or cardiovascular conditions that could interfere with performance. Studies must report time to exhaustion during endurance tests and number of repetitions to failure in muscular resistance tests as primary outcomes, as well as secondary outcomes related to mental fatigue (MF), assessed by validated scales (e.g., VAS). Only studies published in English will be considered, as the language restriction aims to ensure high quality in data extraction and interpretation, minimizing translation bias [31]. Although all researchers involved in data extraction are Brazilian, they are proficient in reading and writing in English, ensuring the reliability of the process. No date restrictions will be applied. Exclusion criteria will encompass non-randomized studies, studies with clinical populations,

interventions without active tDCS or standardized MF induction protocols, investigations that do not report MF and physical performance outcomes, and duplicates or publications with incomplete protocols. The eligibility criteria are detailed below using the PICOS framework:

- Population (P): Physically active adults (recreational or athletes), aged ≥ 18 years, with no neurological, psychiatric, or cardiovascular conditions
- Intervention (I): Active tDCS, applied according to validated protocols targeting any brain region
- Comparator (C): Sham tDCS, with electrodes placed but no current delivered, according to the protocol by Gandiga et al. [32]
- Outcomes (O): Primary — increased time to exhaustion (endurance) and greater number of muscular strength repetitions to failure
- Secondary: Reduction in mental fatigue (VAS score or equivalent scale)
- Study design (S): Randomized controlled trials (parallel or crossover)

### Information sources

The literature search will be conducted exclusively in peer-reviewed journals indexed in the following databases: PubMed/MEDLINE, Embase, Scopus, Web of Science, SPORTDiscus, PsycINFO, and ClinicalTrials.gov. All databases will be searched from inception to the date of the final search (anticipated for November 2025). The date of each search, the specific search strategy, and the number of retrieved records will be meticulously documented in a structured Excel spreadsheet.

### Search strategies

A comprehensive search was conducted in PubMed using four conceptual blocks: (1) transcranial direct current stimulation (tDCS), (2) mental fatigue and cognitive exertion, (3) physical performance outcomes, and (4) a validated filter for randomized controlled trials. The full strategy is detailed below. The final PubMed search was executed on June 11, 2025, yielding 25 records. Equivalent adaptations will be implemented in Embase, Scopus, Web of Science, SPORTDiscus, PsycINFO, and ClinicalTrials.gov. The full PubMed strategy is available in Fig. 1. The full search strategy for all databases is available in S1 File.

Search	Actions	Details	Query	Results
#5	...	>	Search: #1 AND #2 AND #3 AND #4	25
#4	...	>	Search: (randomized controlled trial[pt] OR controlled clinical trial[pt] OR randomized controlled trials[mh] OR random allocation[mh] OR double-blind method[mh] OR single-blind method[mh] OR clinical trial[pt] OR clinical trials[mh] OR ("clinical trial"[tw]) OR ((singl*[tw] OR doubl*[tw] OR trebl*[tw] OR tripl*[tw]) AND (mask*[tw] OR blind*[tw])) OR ("latin square"[tw]) OR placebos[mh] OR placebo*[tw] OR random*[tw] OR research design[mh:noexp] OR follow-up studies[mh] OR prospective studies[mh] OR cross-over studies[mh] OR control*[tw] OR prospectiv*[tw] OR volunteer*[tw]) NOT (animal[mh] NOT human[mh]))	7,973,305
#3	...	>	Search: ("physical performance"[tiab] OR "exercise performance"[tiab] OR "muscular endurance"[tiab] OR "time to exhaustion"[tiab] OR "repetitions to failure"[tiab] OR "resistance training"[tiab] OR "endurance performance"[tiab] OR "exercise capacity"[tiab] OR "total work"[tiab])	59,890
#2	...	>	Search: ("mental fatigue"[tiab] OR "cognitive fatigue"[tiab] OR "brain fatigue"[tiab] OR "mental exhaustion"[tiab] OR "cognitive exertion"[tiab] OR fatig*[tiab] OR "mental exertion"[tiab] OR "cognitive load"[tiab] OR "mental tiredness"[tiab])	154,927
#1	...	>	Search: ("transcranial direct current stimulation"[MeSH Terms] OR "transcranial direct current stimulation"[tiab] OR "tDCS"[tiab])	10,493

Fig. 1 Full PubMed search strategy

### Study selection

All records will be imported into Rayyan software (Rayyan Systems Inc., USA) [33], where duplicates will be automatically removed. Two independent reviewers will screen titles and abstracts. Studies marked as “include” or “uncertain” will advance to full-text evaluation, also conducted independently. Disagreements will be resolved through consensus or, if needed, by a third reviewer. The final manuscript will illustrate the selection process using the PRISMA 2020 flow diagram [34].

### Data extraction

Two reviewers will independently extract data regarding study identification (author, year, country, clinical trial registration), population characteristics (age, sex, physical activity level), MF induction protocol, tDCS parameters (intensity, duration, montage, polarity), sham details, physical performance outcomes (time to exhaustion and repetitions to failure), and MF scores, as well as statistical estimates (means, standard deviations, effect sizes, confidence intervals, *p*-values). Discrepancies will be discussed and, if necessary, resolved by a third reviewer. All decisions will be documented in a structured Excel spreadsheet.

### Data items

A structured spreadsheet will be developed for data extraction, containing predefined fields for all relevant study characteristics and outcomes. Two independent reviewers will extract the data in duplicate, and discrepancies will be resolved through discussion or, if necessary, adjudicated by a third reviewer. The following information will be collected: study design (parallel/crossover), sample size (total and by group), randomization and blinding methods, type of cognitive task used to induce MF, MF measurement tools, technical parameters of tDCS, characteristics of the sham protocol, and all predefined primary and secondary outcomes. When data are not available in the text or tables, authors will be contacted. If necessary, numeric data will be extracted from figures using WebPlotDigitizer, a validated graphical extraction tool. For transparency, the data extraction file will document all extracted values, software version, and parameters (e.g., axis calibration, resolution settings).

### Risk-of-bias assessment

Risk of bias will be assessed using the Cochrane RoB 2.0 tool (Sterne et al.) [35] at the level of each primary outcome (time to exhaustion and repetitions to failure) and the secondary outcome (MF). Two independent reviewers will judge five domains: randomization process, deviations from intended interventions, missing outcome

data, outcome measurement, and selective reporting. A pilot assessment of 5 to 10 studies will be conducted to calibrate the criteria. Disagreements will be resolved by consensus or by a third reviewer. Results will be summarized in tables.

### Data synthesis

When at least three homogeneous studies are available for an outcome, a meta-analysis using a random-effects model (DerSimonian-Laird) will be performed. Mean differences will be calculated for time to exhaustion and standardized effect sizes for repetitions to failure. Heterogeneity will be assessed using Cochran's Q and the  $I^2$  statistic. If heterogeneity is high ( $I^2 > 75\%$ ) or the number of studies is insufficient, a narrative synthesis will be adopted, grouping findings according to MF protocol characteristics, tDCS parameters, and participants' activity levels. Pre-specified subgroup analyses (athletes vs. nonathletes; anodal vs. cathodal stimulation) and sensitivity analyses (excluding studies with high risk of bias) will be conducted. An exploratory meta-regression will be performed if  $\geq 10$  comparable studies are available.

### Certainty of evidence

The strength of the body of evidence for the primary outcomes will be assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach. This evaluation will consider five domains: risk of bias, inconsistency, indirectness, imprecision, and publication bias. Two reviewers will independently apply the GRADE criteria, and disagreements will be resolved by consensus or adjudicated by a third reviewer. A summary of findings (SoF) table will be developed to present each primary outcome's GRADE ratings and key outcome data.

### Discussion

This protocol establishes a rigorous and transparent methodology for conducting a systematic review of tDCS in physically active adults, emphasizing enhancing physical performance and reducing mental fatigue. By prioritizing primary outcomes, precisely time to exhaustion and the number of repetitions to failure, and restricting inclusion to randomized controlled trials, we aim to maximize comparability between studies and the validity of the findings. The resulting synthesis is expected to support the standardization of tDCS protocols in sports and exercise settings.

However, certain limitations inherent to the study design must be acknowledged. The decision to include only studies published in English may exclude relevant evidence available in other languages, and the variability in tDCS technical parameters (such as intensity,

duration, and electrode montage), as well as in mental fatigue induction protocols, may introduce heterogeneity that limits the feasibility of conducting meta-analyses. To mitigate these issues, we will implement sensitivity analyses, subgroup analyses, and exploratory meta-regression, in addition to carefully assessing the risk of bias and the quality of evidence using the GRADE approach. The findings of this review may provide a foundation for developing standardized, evidence-based tDCS protocols to enhance physical performance and mitigate mental fatigue in athletic populations. This could directly support coaches, clinicians, and sports scientists in implementing safe and effective brain stimulation strategies to optimize performance in training and competition environments. Ethical approval from a Research Ethics Committee is not required as this literature review is based on previously published studies. In this way, we aim to address the identified methodological gap and foster collaboration and transparency in future research on tDCS, mental fatigue, and physical performance.

**Abbreviations**

DLPFC	Dorsolateral prefrontal cortex
GRADE	Grading of Recommendations Assessment, Development and Evaluation
MF	Mental fatigue
M1	Primary motor cortex
PRISMA-P	Preferred Reporting Items for Systematic review and Meta-Analysis Protocols
RCT	Randomized controlled trial
RoB 2.0	Risk of bias 2.0 tool
RPE	Rating of perceived exertion
tDCS	Transcranial direct current stimulation
VAS	Visual analogue scale

**Supplementary Information**

The online version contains supplementary material available at <https://doi.org/10.1186/s13643-025-02916-x>.

- Supplementary Material 1: S1 File. Full Search Strategy for All Databases.
- Supplementary Material 2: S2 File. PRISMA-P Checklist.
- Supplementary Material 3: S3 File. Data Extraction Form.

**Acknowledgements**

We thank the Faculty of Physical Education and Dance (FEFD) of the Federal University of Goiás and IF Goiano for their support.

**Authors' contributions**

All authors contributed equally to this work. Therefore, all authors conceptualized the project, drafted the protocol, registered it, contributed to its development, and critically read and gave final comments.

**Funding**

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasil (CAPES) — Finance Code 001.

**Data availability**

The data generated and analyzed during this study will constitute the resulting systematic review article.

**Declarations**

**Ethics approval and consent to participate**

Ethics approval is not required for a systematic review of publicly available literature.

**Consent for publication**

This study uses secondary (published) data; as such, consent will not be required.

**Competing interests**

The authors declare that they have no competing interests.

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Received: 16 June 2025 Accepted: 8 July 2025

Published online: 25 September 2025

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